Cosmic-Ray Muon Radiography for Homeland Defense

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The threat of the detonation of a nuclear device in a major U.S. city has prompted research aimed at providing more robust border surveillance for contraband SNM. Existing radiographic methods are not only inefficient for the detection of shielded SNM but also involve radiation hazards. Members of P-25 in collaboration with NIS Division have invented a new method that could detect small quantities of shielded SNM in a short time using the natural process of multiple scattering of cosmic-ray muons as a radiographic probe (Figure 1). A chief advantage of this new method is that no artificial radiation dose is applied to the object being examined. We are currently examining how well the method works for complex homeland defense scenarios.

Cosmic-Ray Muons and Multiple Coulomb Scattering

The earth's atmosphere is continuously bombarded by primary cosmic rays, which are energetic stable particles, mostly protons (Figure 2). Interactions between these protons and atmospheric nuclei produce a shower of secondary cosmic rays, including many short-lived pions. These pions decay quickly to muons, which interact with matter primarily through the Coulomb force and have no nuclear interaction. The Coulomb force, which involves the attraction or repulsion of particles or objects because of their electric charge, removes energy from muons more slowly than nuclear interactions would. Therefore, muons can travel a great distance through the atmosphere. Some muons decay to electrons. There are other particles generated in the cascade, but the remnant of the secondary cosmic-ray cascade at the earth's surface is 90% comprised of muons.

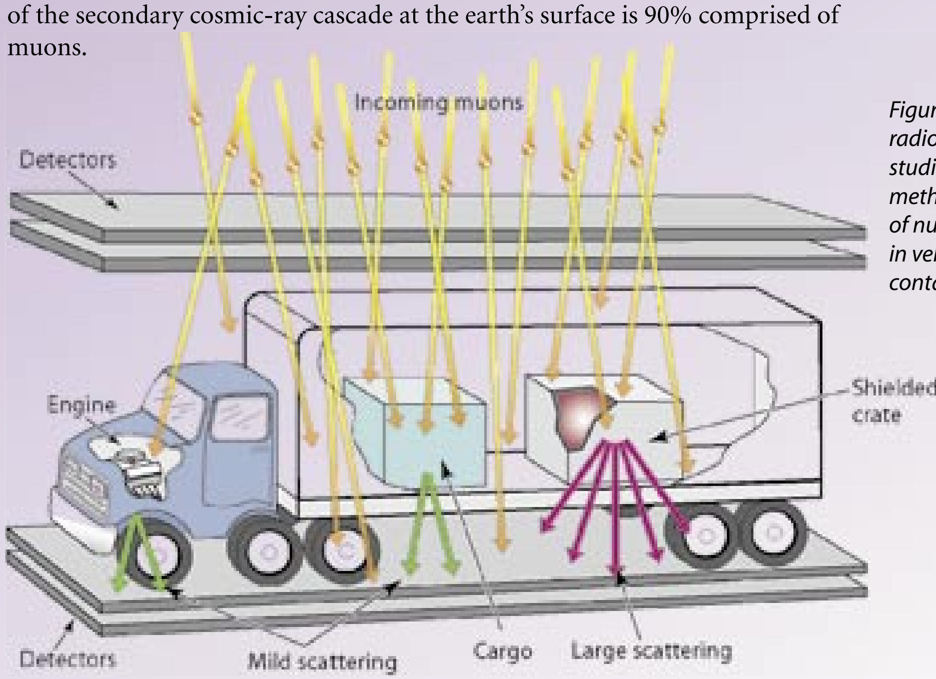


Figure 1. Cosmic-ray muon radiography is being studied as a potential method for the detection of nuclear contraband in vehicles and shipping containers.

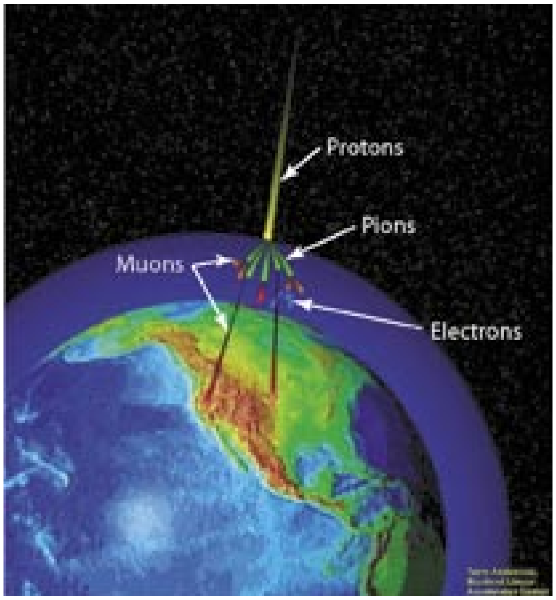


Figure 2. Illustration of the atmospheric cosmic-ray particle cascade.

Consequently, the earth's surface is showered constantly by muons in the form of penetrating, weakly interacting charged radiation. Because about 10,000 muons per minute pass through each square meter of area (arriving from angles spanning the upper hemisphere), this shower of free particles was naturally considered as a radiographic probe. The mean momentum of muons at sea level is about 3–4 GeV/c, which allows them to penetrate through meters of rock. Because the momenta spectrum of the muons is continuous and the average range is long, differential attenuation can be used to radiograph large objects. In the late 1960s, Luis Alvarez placed muon counters below the Second Pyramid of Giza and used differential attenuation to search for hidden chambers within the structure.[1] Researchers continue to perform this type of radiography on large manmade and geographic structures.

Calculating Uncertainty

One can calculate the uncertainty in this sort of radiography. The number of transmitted particles is $N = N_0 \exp(-L/\lambda)$, where λ is the mean-free path, N_0 is the number of incident particles, and L is the depth of the material. The uncertainty in measuring L by counting transmitted particles is $\Delta L = \lambda/\sqrt{N}$. A 1,000-cm^3 volume of uranium would receive an incident flux of 100 muons in one minute. Because the mean-free path of cosmic-ray muons in uranium is on the order of 1 m, the thickness of a 10-cm cube of uranium could be determined to a precision of about its thickness.

Differential attenuation has proven useful for examining very large structures, but we make use of a different interaction between charged particles and matter to enable radiography of much smaller objects. A charged particle (such as a proton, electron, or muon) passing through material is deflected by many small-angle Coulomb scatterings off the nuclei of the atoms that make up the material. The particle will traverse the material in a stochastic path because of these multiple scatterings, and it will emerge at an angle scattered from the original track. The average scattering angle is distributed approximately Gaussian, and the mean-square scattering angle is strongly dependent on the material's Z number (i.e., atomic number, the elements in the periodic system are arranged in order of increasing number of protons in the nucleus) (Figure 3). There is a fairly clear distinction between the scattering from muon passage through common low-, medium-, and high-Z materials.

The width of the scattering distribution of muons is related to the scattering material as

$$\sigma_0 \cong \frac{15}{p}\sqrt{\frac{L}{L_{rad}}},$$

where p is the particle momentum and L_{rad} is the radiation length. If the muon scattering angle in an object can be measured and if its momentum is known, then the material depth can be measured to a precision of $\Delta L/L = 1/\sqrt{N}$, where N (the number of transmitted muons) is very nearly equal to the number incident. Thus each transmitted muon provides information about the thickness of the object with a precision that is smaller than the thickness of the object. For the 10-cm^3 cube of uranium, for example, the uncertainty is 10% in one minute of exposure rather than the 100% that could be obtained with differential attenuation radiography. This analysis demonstrates the enormous advantage of multiple-scattering muon radiography for this application.

Cosmic-Ray Muon Radiography—Experimental and Simulated Results

To make use of the information carried by scattered muons to probe an object, we tracked individual muons into and out of a target volume wherein objects to be radiographed are placed. (This work was carried out on Line B at LANSCE.) The scattering angle of each muon is measured, and we use tomographic methods to reconstruct the structure and composition of the objects. To demonstrate proof of principle, we constructed a small experimental apparatus built with a set of four position-sensitive drift chambers. Two groups of detectors, each measuring particle position in two orthogonal coordinates, were placed above an object volume; two other groups of detectors were placed below. The position resolution of these detectors was measured to be about 400-μm FWHM. Each radiograph of two small test objects shown in Figure 4 was made using the information carried by about 100,000 scattered muons. Several hours were required to produce the remarkable detail in these images using our small, relatively inefficient prototype. In a contraband detection scenario, only one or two minutes might be available for inspection. Fortunately, detection of shielded 5- to 10-cm-diam SNM objects requires many fewer muons. Moreover, the cosmic-ray muon momentum spread increases the uncertainty of the scattering signal in the experiment; however, we did not measure the muon momentum.

We have proposed a method of estimating muon momentum in an effort to further reduce exposure time. In this method, muon scattering is measured through plates of material of known depth and composition positioned below the object volume. To test this method, we developed a simulation code that generates cosmic-ray muons with the appropriate distribution of energies and angles, propagates them through a test volume, and generates the positions at which they would be detected in four detector planes. The muon spectrum, angular distribution, and rate were appropriate for sea level. A detector position resolution of 400-μm FWHM was simulated, and the simulation was validated against the experimental results. Momentum measurement to about 50% precision was assumed.

We have examined numerous simulated scenarios wherein SNM contraband is placed within shipping containers that are hidden within various background cargos. Figure 5 presents the results of one of these simulations using a reconstruction method optimized for detecting high-Z material in medium-Z surroundings. A steel-walled cargo container containing 12 tons of distributed iron parts was simulated. One small lead-shielded container carrying a small amount of plutonium was placed within the cargo. The contraband is clearly visible in the one-minute simulated radiograph.

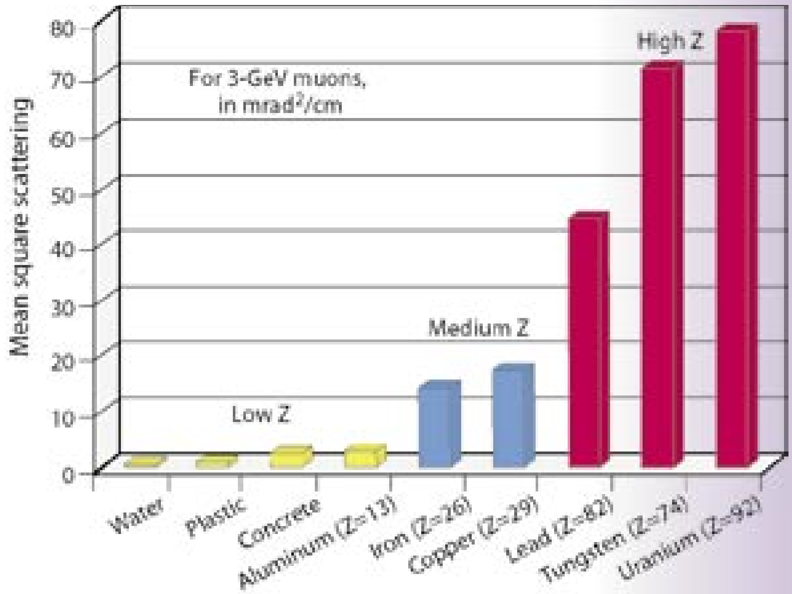
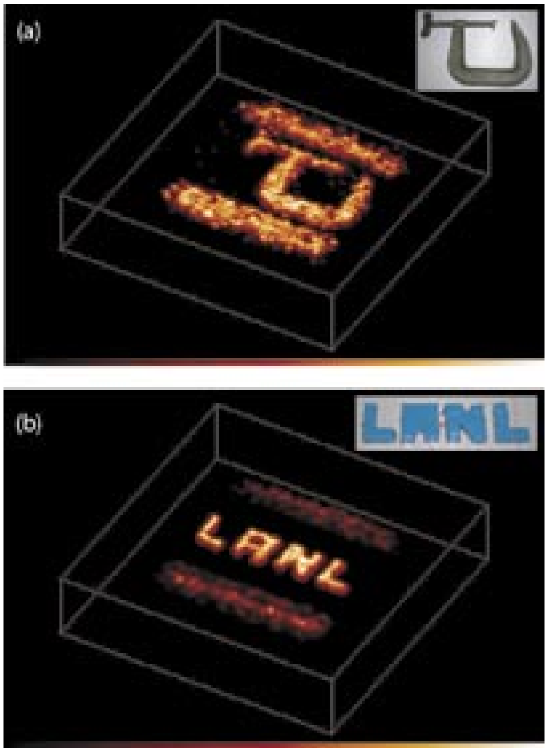


Figure 3. The scattering of muons passing through material varies strongly with the Z number of the material.

Figure 4. Experimentally produced cosmic-ray muon radiographs of (a) a steel c-clamp and (b) the acronym "LANL" constructed from 1-in.-lead stock. The bar-like features visible on either side of the images result from steel beams used to support a plastic object platform.



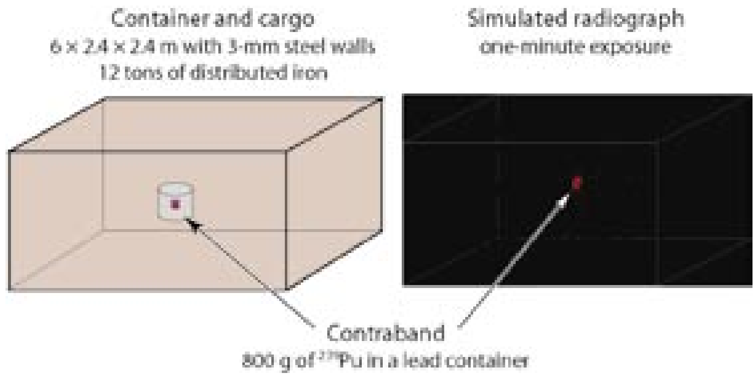


Figure 5. Simulation of a steel-cargo container with SNM contraband buried within iron (left) and a one-minute cosmic-ray muon radiograph (right).

Conclusion

We have developed and experimentally demonstrated a unique radiography method using the multiple-scattering process of cosmic-ray muons. This method, which is particularly sensitive to high-Z dense materials, may prove useful in detecting smuggled cargoes of SNM in incoming vehicles and commercial traffic at U.S. borders in short times with no additional radiation dose to vehicle occupants or border guards. Our current efforts are devoted to confirming our small-scale experimental and full-scale simulated results with a full-scale experimental demonstration; to developing low-cost, field-deployable detectors; and to optimizing our information-processing methods.

References

1. L.W. Alvarez *et al.*, "Search for hidden chambers in the pyramids," *Science* **167**, 832-839 (1970).

Acknowledgment

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